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13. ABSTRACT (Maximum 200 words)

The Target Reflectivity Frequency Response is estimated through an extension of the MUSIC-PISARENKO technique. Density function estimation will enable passive sensors to sort incoming angles and frequency. Time variation tracking is provided as an alternative to adaptive beam-forming. Noise is taken fully into consideration. Wavelet and Garbor filters applied to range doppler density evaluation.

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Final Report to the AFOSR on the research grant "Adaptive Estimation and Approximation of Continuously Varying Spectral Density Functions to Airborne Radar"

F49620-92-J-0044

by

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November 15, 1992

A summary and the details of the research performed under this grant can be found in Attachment 1 (A Summary of Recent Topics of Research Results on Signal Processing) and in Attachment 2 (a listing of the research items).

Some additional work is detailed in the following reports to Rome Laboratory which were all sent to Dr. Jon Sjogren who was the Program Manager for this grant.

During 1992-93 the principal investigator was a resident at the Rome Laboratory (URRP Program) and the result of the work is the Reports to the Rome Laboratory listed in Attachment 2.

Attachment 1

A Report to Rome Laboratory

(1992-4a)

A SUMMARY OF RECENT TOPICS OF RESEARCH RESULTS ON SIGNAL PROCESSING

by

E. Emre

Supported by the AFOSR

A Report to Rome Laboratory

(1992-4a)

A SUMMARY OF RECENT TOPICS OF RESEARCH RESULTS ON SIGNAL PROCESSING

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*Supported by AFOSR.

0. SUMMARY OF TOPICS FOR ARRAY PROCESSING

1. TARGET DENSITY FUNCTION ESTIMATION VIA DIRECT TECHNIQUES (VIA STANDARD SIGNALS AND ARRAYS)

Provides an image of the target area in terms of the reflectivity of each point to a physically monochromatic (or very narrowband) signal, such as a continuous sine wave, or a train of constant amplitude pulses modulating a sine wave (carrier). Hence target identification/detection is possible via analysis of this image.

TWO MAIN TYPES:

1a. **Time-invariant** (with or without doppler shifts). Doppler shift models the velocity of targets assumed to move with constant velocity.

1b. **Time-varying:**

As targets move, the reflectivity of each point in space varies with time.

Estimation of a time-varying target density function provides

i) A movie picture of the target area by as many snapshots per time interval as desired

ii) Multitarget Tracking at the signal processing level. Replaces Adaptive Beamforming for Tracking

2. TARGET DENSITY FUNCTION ESTIMATION AND ANALYSIS VIA WAVELET AND GABOR THEORY

Provides multiresolution spectral analysis of the target density function (image).

Also, provides new techniques for beamforming.

3. TARGET REFLECTIVITY FREQUENCY RESPONSE (TRANSFER FUNCTION) AND/OR IMPULSE RESPONSE ESTIMATION AT EACH ANGLE SIMULTANEOUSLY.

These quantities are well known to be target signatures.

At a fixed range (determined via such as pulse timing) one can determine these quantities at each angle simultaneously, being able to identify each target simultaneously.

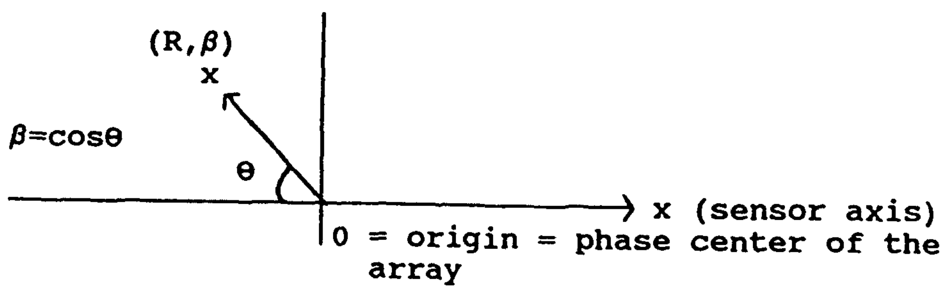
4. ANGLE-FREQUENCY DENSITY FUNCTION ESTIMATION

These techniques enable passive sensors to sort the incoming signals at each angle and frequency continually.

Techniques are also developed to determine dominant (point) angles, frequencies as extensions of MUSIC-PISARENKO type techniques.

1. TARGET DENSITY FUNCTION ESTIMATION VIA DIRECT TECHNIQUES

Consider the space in terms of (range=R, β=directional cosine) coordinates.



Suppose the transmitted signal is

$$W(t) = e^{j\omega_c t},$$

or

$$W(t) = e^{j\omega_c t} p(t),$$

where

p(t) = a train of pulses of constant amplitude.

The reflection to the phase center from a very small area characterized by $(R, R+\Delta R)$ and $(\beta, \beta+\Delta\beta)$ is approximately

$$\tilde{h}(R,\beta) W(t-\frac{2R}{c}) \quad (R\Delta\beta) \quad (\Delta R)$$

(c = speed of the waves)

The set of reflectivity constants

$$\tilde{h}(R,\beta)$$

for each R,β provides an image of the target area. As $\Delta R \to 0$, $\Delta\beta \to 0$ the total reflected signal to the phase center is

$$(1) \quad y(0,t) = \int_{-1}^{1} \int_{0}^{R_1} h(R,\beta) W\left(t-\frac{2R}{c}\right) R\,dR\,d\beta$$

where

$$h(R,\beta) = \lim_{\substack{\Delta R \to 0 \\ \Delta\beta \to 0}} \tilde{h}(R,\beta),$$

and

R_1 = maximum range from which there is a reflection.

For simplicity any known function of R such as due to medium, integral multiplier, etc. will be included as a factor of $h(R,\beta)$, and we will rewrite (1) as

$$(2) \quad y(o,t) = \int_{-1}^{1} \int_{0}^{R_1} \underbrace{h(R,\beta)}_{\text{Target Density Function}} W\left(t-\frac{2R}{c}\right) dR\,d\beta.$$

The sensor at point x receives

$$(3) \quad y(x,t) = \int_{-1}^{1} \int_{0}^{R_1} h(R,\beta) W\left(t - \frac{2R}{c} - \frac{\beta x}{c}\right) dR d\beta.$$

Thus, the function

$h(R,\beta)$ = Target Density Function, provides an image of the Target area.

If the target area changes with time, then, the reflectivity of each point (β,R) varies with time. This time-varying reflectivity is represented by the

$h(t;\beta,R)$ = Time-varying target density function.

Thus, if $h(t,\beta,R)$ can be estimated for each t, or for as many values of t as desired per processing interval, a movie picture of the target area is obtained with as many measurements for each target point per time interval as desired. Thus, this provides MULTI-TARGET TRACKING with no need for a posteriori DATA-ASSOCIATION.

Also, provides an alternative to Adaptive Beamforming for tracking.

An alternative (restrictive) way of modeling time-variance is in terms of doppler shift. This gives rise to range-angle-doppler target density function

$h(\omega,R,\beta)$ with ω = a particular doppler frequency corresponding to a target at (R,β) whose velocity is constant and yields ω as a doppler shift.

COMPARISON TO PREVIOUS WORK ON TARGET DENSITY FUNCTION ESTIMATION

i) Mostly considers density functions in range-doppler coordinates $h(\omega,R)$, only.

ii) Most such techniques require transmission of many signals (to form a basis)

iii) The concept of a truly time-varying density function appears in range coordinates, $h(t,R)$; with no general estimation technique given.

We have developed techniques to estimate target density functions viewed as totally unknown apriori

i) In Range-Angle-Doppler coordinates, $h(\omega,\beta,R)$,

ii) Using one standard radar signal and an array.

iii) Also, we have developed techniques to estimate the truly time-varying target density functions

$h(t,\beta,R)$.

FURTHERMORE, NOISE IS TAKEN INTO FULL CONSIDERATION SEPARATELY.

We have developed techniques for estimation in the presence of noise (e.g., receiver noise). Our target density function estimation techniques utilize Fourier series coefficients of the reflected signal. When there is noise, we obtain the MINIMUM VARIANCE estimate of these coefficients (can be done recursively and adaptively using a Kalman filter).

If the S/N ratio is already high, one pulse is sufficient for target density function estimation.

2. WAVELET AND GABOR THEORY FOR ESTIMATION AND ANALYSIS OF TARGET DENSITY FUNCTIONS AND FOR BEAMFORMING

A slight modification of the usual wavelet theory is more suited to array processing.

A wavelet $W(t)$ is a function where its Fourier transform $\tilde{W}(\omega)$ satisfies

$$\gamma_W := \int_{-\infty}^{\infty} \frac{\tilde{W}(\omega)\tilde{W}^*(\omega)}{|\omega|} d\omega < \infty.$$

If $h(\beta)$ is the angular target density function at a fixed range R (assumed to be 0 for simplicity), and if $W(t)$ is transmitted, the sensor at point x receives

$$y(x,t) = \int_{-1}^{1} g(\beta) W(t-\beta x)\, d\beta.$$

(take c=1 for simplicity)

Since $g(\beta)=0$ for $\beta \notin (-1,1)$,

$$y(x,t) = \int_{-\infty}^{\infty} g(\beta) W(t-\beta x)\, d\beta$$

= (MODIFIED) WAVELET TRANSFORM OF $g(\beta)$.

It can be shown that

$$g(\beta) = \frac{1}{\gamma_W} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} y(x,t) W^*(t-\beta x)\, dx dt$$

= INVERSE TRANSFORM

This can be applied to

$h(R,\beta)$ = joint range-angle target density function

with respect to β.

MULTIRESOLUTION ANALYSIS

$$Y(x,\omega) = \mathcal{F}\{y(x,t)\} = \tilde{W}(\omega) H(\omega x)$$

where

$$H(\omega) = \mathcal{F}\{h(\beta)\}.$$

Thus, sensor coordinate x is the dilation parameter for <u>multiresolution</u> spectral analysis of $h(\beta)$.

SOME OTHER RESULTS

i) $h(R,\beta)$ can be estimated as a Fourier series with respect to a wavelet

ii) very easy to perform beamforming.

iii) it is enough to have finite aperture (for the array), and finite observation time. Hence, totally practical.

One can also use <u>Gabor theory</u> to estimate $h(\beta,R)$ and spectral analysis with respect to R. Many results (like the above for wavelet theory) are possible.

3. TARGET REFLECTIVITY IMPULSE RESPONSE AND/OR TRANSFER FUNCTION (SPECTRUM) ESTIMATION AT EACH ANGLE SIMULTANEOUSLY

It is known that target reflectivity is frequency dependent. For a fixed range, if $R(\omega,\beta)$ is the frequency dependent reflectivity at the angle β, techniques are developed to estimate $R(\omega,\beta)$ as a function of (ω,β). $R(\omega,\beta)$ is the signature of the target at angle β. Also, techniques are developed to estimate

$r(t,\beta)$ = reflectivity time response of the target at angle β to an impulse.

Clearly, in linear mode,

$$R(\omega,\beta) = \mathcal{F}(r(t,\beta)).$$

Medium transfer function is also taken into consideration.

One can either estimate $r(t,\beta)$ or $R(\omega,\beta)$ directly, for each β siumultaneously.

4. DIRECTION-FREQUENCY DECOMPOSITION OF SIGNALS RECEIVED BY AN ARRY (PASSIVE SENSORS)

Two main types of results are obtained.

i) One can express the incoming signal to sensor at the point x as

$$y(x,t) = \int_{-1}^{1} \int_{-\infty}^{\infty} a(\beta,\omega) e^{j\omega(t-\beta\frac{x}{C})} d\omega d\beta.$$

Thus

$a(\beta,\omega)$ is the <u>direction-frequency density function</u>.

Techniques are developed to estimate $a(\beta,\omega)$ for all (β,ω).

ii) One may be interested in dominant directions β for a given ω, as well as dominant frequencies ω for a given direction β.

Techniques are developed to estimate dominant directions and frequencies, as extensions of MUSIC-PISARENKO type techniques.

<u>NOTE</u>: i) is shown to be dual to the problem of wave-beamform design: i.e., find

$f(t,x)$ = the signal to emit from the sensor at point x, such that in each direction a possibly different signal is sent from the array. i.e., the points at the angle β at time t receive the <u>wave-beam form</u>

$W(t,\beta)$ = either a prespecified desired function, or an approximation to it.

Attachment 2

Report to Texas Instruments 1992 Series a:

2a) A New Approach to Arrays of Sensors

3a) Simultaneous Wave-Beam form Design and Angle-Frequency Density Function Estimation (Temporal) And Spatial Decomposition

Report to Texas Instruments 1992 Series b:

1b) Estimation Of Target Density Functions In Space (Range-Angle)- Doppler Coordinates

2b) Range-Direction-Doppler Target Density Function Estimation By Passive Beamforming

3b) Joint Range-Angle Beamforming With Application To Estimation Of Target Density Functions

4b) Estimation Of Time-Varying Range- Direction Target Density Functions In Nonstationary Environments

Report to Texas Instruments Series c:

1c) Estimation and Multiresolution Analysis Of Angular and Range-Angle Target Density Functions/ Beamforming Via Wavelet Theory

2c) Estimation And Analysis Of Range (Range-Angle) Target Density Functions Via (A Modified) Gabor Theory

Report To Rome Laboratory 1992

1) Signal Estimation Techniques For Target Density Function Estimation In The Presence Of Noise

2) A Technique For Estimation Of Fourier Series Coefficients (And Samples) Of A Signal From It's Noisy Samples Forming The Usual FFT Bins

3) Virtual Sensors (Samples) With Application To Beamforming (Frequency Filtering) And Approximation Of A Continuously Distributed Sensor (Continuous Function) By Point Sensors (Time Samples)

4) Remarks On Standard (Physical) Radar Signals And Their Fourier Series Representation For Target Density Function Estimation

5) A Summary Of Work On Target Density Function Estimation

6) Physical Existence Of Target Density Functions

7) Existence Of Time-Varying Target Density Functions In Nonstationary (Time-Varying) Environments

8) Estimation Of Angular Target Reflectivity Spectra (Transfer Functions)

9) A Direct Technique For Estimation Of Angular Target Reflectivity Impulse Response Density Function

10) Range-Angle Target Density Function Estimation Via A Narrow Band Signal

11) A New Technique For Estimation Of Time-Varying Target Density Functions In Nonstationary(Time-Varying) Environments

Reports to Rome Laboratory 1992 Series a:

1a) Estimation And Analysis Of Target Density Functions Via Wavelet And Gabor Theory

2a) A Summary Of Two Techniques For Time-Varying Target Density Function Estimation

3a) Advantages Of (Time-Varying) Target Density Functions For Radar Signal Processing

4a) A Summary Of Recent Topics Of Research Results On Signal Processing

Rome Reports 1993

1) A Modification To Certain Target Density Function Estimation Techniques

1a) A Summary Of Certain Extrapolation Techniques In The Presence Of Noise